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RISK ANALYSIS OF SPACE TRANSPORTATION DURING THE SPACE STATION ERA

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STUDY OUTLINE

This study addresses the operational risks of manned space transportation during the era of space station deployment along with alternative launch vehicle architectures to reduce the risks. Vehicle architectures considered include Shuttle only, an additional unmanned launch vehicle, and a second manned/unmanned launch vehicle.

Projections are made for the operational parameters and flight event probabilities. Using these projections and Space Station era mission models, the operability of alternative vehicle architectures are examined, and implications to future manned space program plans are summarized.

STUDY OUTLINE

- Study Objectives and Candidate Transportation Systems
- Derivation of Ascent, Abort and Orbit/Return Event Probabilities
- Space Station Era Mission Models
- Space Transportation Systems Operability Analyses
- Summary

STUDY OBJECTIVES

The risks associated with the U.S. Manned Space program during the deployment of the space station can be quantified in terms of three major objectives during that period, i.e., to provide 1) a high probability of successful deployment of one-of-a-kind Space Station modules and other major space systems, 2) safe, economically viable manned space operations and 3) operational capabilities adequate to support the mission model.

To quantify the success of any vehicle architecture in achieving these objectives, five parameters are highlighted: 1) the probability of mission success, 2) the probability of payload loss, 3) the probability of Orbiter or other manned vehicle loss, 4) the expected successful launch rate for a given planned launch rate, and 5) the launch vehicle availability, i.e., the fraction of time that a launch vehicle is available for launch of time-critical payloads.

STUDY OBJECTIVES

The objectives of this study are to assess the risks of the Manned Space program in the Space Station era with and without Shuttle augmentation with Unmanned and Manned Launch Vehicles, specifically projecting the probabilities of

- o Mission Success
- o Payload Loss
- o Orbiter (or other Manned Vehicle) Loss
- o Planned Launch Rates vs Successful Launch Rate
- o Launch Vehicle Availability

CANDIDATE TRANSPORTATION SYSTEMS

Several launch fleets were analyzed in this study: Shuttle only, Shuttle supported by one of two Shuttle-C (SHC) vehicles, and Shuttle supported by an Independent Launch Vehicle (ILV), i.e., with subsystems totally independent of those of Shuttle. Initially, the supporting launch vehicles were assumed to be unmanned only. Subsequently, analyses were performed assuming that either the SHC3 or the ILV would launch cargo and a manned vehicle with the capability of providing emergency escape and rotation for the Space Station crew. The manned vehicle could be either a capsule or a lifting body within the range of concepts being explored for the Assured Crew Rescue Capability (ACRC) and the Personnel Launch System (PLS). For manned SHC and ILV launches, it is assumed that major cargo elements would be carried external to the manned vehicle and therefore not recovered in an abort situation.

CANDIDATE TRANSPORTATION SYSTEMS

- Shuttle only

- Shuttle plus 2 SSME Shuttle-C (SHC2)

- Shuttle plus 3 SSME Shuttle-C with engine-out capability for mission success (SHC3), manned and unmanned

- An Independent Launch Vehicle (ILV) having the same performance and operational characteristics as SHC3, manned and unmanned

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DERIVATION OF ASCENT, ABORT AND ORBIT/RETURN EVENT PROBABILITIES

HISTORICAL DATA BASE

The subsystem failure probabilities used in this study are projections based upon the most up-to-date U.S. Launch vehicle failure histories for Saturn, Titan, Atlas, Delta and Shuttle.

The data base used was initially compiled by Marshall Space Flight Center and is currently being expanded by Sparta and L Systems under an Air Force contract.

HISTORICAL DATA BASE

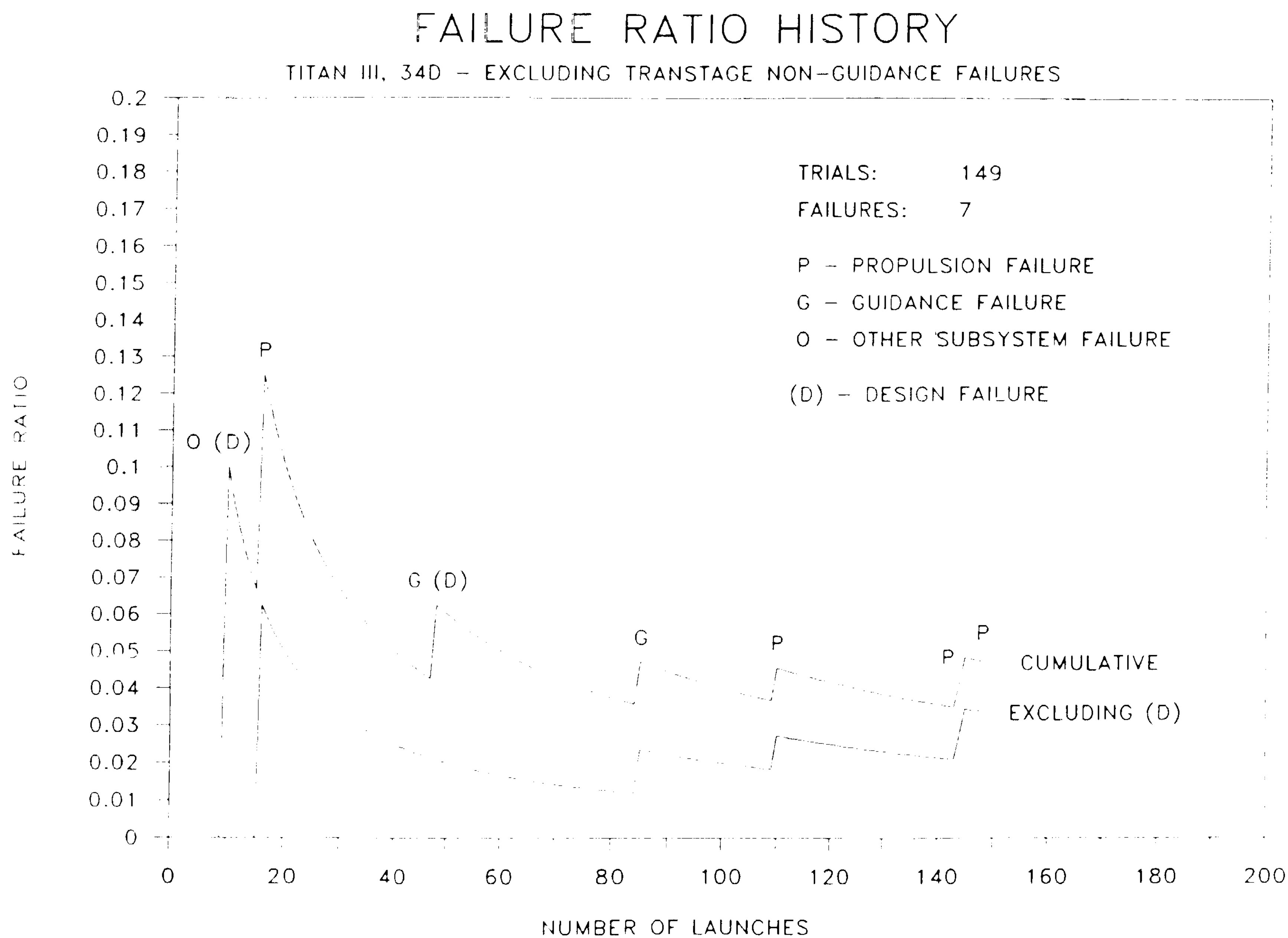
- o MSFC Launch Experience and Engine Data Bases
  - / All U.S. Space Launches
  - / Engine - Ground Test and Flight
- o Expanded and correlated by Sparta
  - / Additional Ballistic Missile and Sounding Rocket History
  - / Solids Data Base - Astronautics Laboratory
  - / Additional Details on Flight Anomalies
  - / Foreign Launches, Including Classified Data

FAILURE RATIO HISTORY
TITAN III, 34D - EXCLUDING TRANSTAGE NON-GUIDANCE FAILURES

Because of the statistically small sample sizes available, launch vehicle failure probability (one minus the vehicle reliability) is best described in terms of the failure ratio: the number of failures divided by the number of launches. The plot presents two cumulative failure ratio curves for the Titan launch vehicle family, one showing total failures and one, with the design failures deleted, showing processing failures only. Both demonstrate learning (a decreasing failure ratio with time) and both have leveled off. The design failures, which occurred early, can be removed to show that processing failures limit the failure ratio which ranges between 0.02 and 0.04. (The 50 point moving average indicates a possible trend to a higher failure ratio as a result of recent failures. This trend is probably due to the going-out-of-business environment in which the expendable launch vehicle fleet operated through most of this decade.)

Similar maturing trends are evident in the Atlas and Delta launch vehicle family histories, indicating that similar factors constrain all three systems. These systems include single-string, non-redundant subsystems, ballistic missile design-margin heritage, and complex labor-intensive processing. The leveling out of launch vehicle failure probability indicates a multiplicity of failure modes, that is, for each process corrected after a failure, many other processing failure modes remain. Unless failure-tolerant designs and tighter processing controls are incorporated, the failure ratio probably will remain in its present range.

Tracking failure ratio histories by subsystem and projecting future improvements provides a basis for estimating the failure probabilities of new or highly modified launch systems.


FAILURE RATIO HISTORY
TITAN III, 34D - EXCLUDING TRANSTAGE NON-GUIDANCE FAILURES
TRIALS: 149
FAILURES: 7
P - PROPULSION FAILURE
G - GUIDANCE FAILURE
O - OTHER SUBSYSTEM FAILURE
(D) - DESIGN FAILURE
O (D)
P
G (D)
G
P
P
P
CUMULATIVE
EXCLUDING (D)
FAILURE RATIO
0.2
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
20
40
60
80
100
120
140
160
180
200
NUMBER OF LAUNCHES

LIQUID PROPULSION FAILURE HISTORY FOR U.S. SPACE LAUNCH VEHICLES

Because propulsion system failures have been the largest contributors to launch vehicle failures, the flight failure history was analyzed to determine where in the system failures occurred. Specifically, engineering judgments were made for each failure as to whether the failure was in the engine or in "other" propulsion subsystems outside of the engine. A listing and description of the failures is presented in this chart.

LIQUID PROPULSION FAILURE HISTORY FOR U.S. SPACE LAUNCH VEHICLES

VEHICLE	ENGINE	TOTAL FLIGHTS	NO. ENGINES	FAILURE MO. YR.	DESCRIPTION	ENGINE OR OTHER?
CRYOGENIC ENGINES						
CENTAUR	RL-10	69 1)	2	6/64	LOSS OF C2 HYDRAULIC POWER - MECH. FAILURE AT TURBOPUMP	O
				4/66	LOSS OF H2O2 PRECLUDED SUCCESSFUL MES2 - LEAK IN RCS	O
				8/68	MES2 NOT ACHIEVED - LO2 LEAK FREEZING H2O2 LINES	O
				2/74	LO2 BOOST PUMP FAILED TO OPERATE FOR MES1	O
				6/84	LO2 TANK LEAK - ANOMALOUS SEPARATION & FIRST BURN	O
SATURN I	RL-10	9	6	-/-	NO FAILURES	
SATURN V	J2	13 2)	6	4/68	INJECTOR BURN THROUGH - POSSIBLE FUEL LINE FAILURE 3)	E?
				4/68	ERRONEOUS ELECTRICAL SIGNAL 3)	O?
				4/68	FUEL LINE FAILURE - LH2 LEAK IN ENGINE COMPARTMENT 3)	E?
				4/70	PREMATURE CUTOFF 3)	E?
SHUTTLE	SSME	26	3	7/85	TEMP. SENSOR - MANUAL OVERRIDE OF 2ND SHUTDOWN 3)	E
NON-CRYOGENIC ENGINES						
ATLAS	MA-2/MA-3	101 4)	3	3/65	BOOSTER FUEL PRE-VALVE INADVERTENTLY CLOSED	O
				9/77	BOOSTER GENERATOR HOT GAS LEAK - ENGINE DUCTING CRACK	E
				12/80	BOOSTER LUBE OIL LOSS	E
				12/81	BOOSTER GAS GENERATOR FUEL COOLING PORTS CLOGGED	E
DELTA	RS-27/AJ-10	181	2	8/69	FIRST STAGE HYDRAULIC (GIMBAL) FAILURE	O
				7/73	SECOND STAGE HYDRAULIC (GIMBAL) FAILURE	O
SATURN I	H-1	19	7	5/64	TURBOPUMP FAILURE 3)	E
SATURN V	F-1	13	5	-/-	NO FAILURES	
TITAN	LR-87/LR-91	149	3	4/67	GROSS CONTAMINATION IN PROPELLANT LINE	O
				3/78	TURBINE DRIVEN HYDRAULIC PUMP OVER PRESSURE	O
				8/85	MASSIVE OX LEAK	O

1) EXCLUDES NO TRIALS DUE TO LV FAILURE
2) PLUS 9 SATURN IB (1 PER LAUNCH)
3) MISSION SUCCESS OR PARTIAL SUCCESS BECAUSE OF ENGINE-OUT CAPABILITY
4) ATLAS WITH CENTAUR ONLY PRIOR TO 5/75, ALL ATLAS LAUNCHES THEREAFTER

LIQUID PROPULSION FLIGHT HISTORY
FAILURE RATIOS

The results of the liquid propulsion flight failure history analysis are presented on this chart. Utilizing mean values for both cryogenic and non-cryogenic engines, it was found that two thirds of all propulsion system failures occurred in subsystems other than the engine. Thus, failure analyses based upon engine data only will lead to erroneous results. Accordingly, failure probabilities utilized in this study will be for the entire propulsion subsystem, not engine only.

Additionally, it was found that the failure ratio for cryogenic engines is about double that for non-cryogenic engines. Investigations directed toward understanding the reasons for this difference could be rewarding with respect to reducing the probabilities of engine failures. However, an immediate question which occurs is whether failure probabilities should be calculated on a per engine or per stage basis. This is addressed on the next chart.

LIQUID PROPULSION FLIGHT HISTORY
FAILURE RATIOS

Engine Flights	% Failures: Engines	% Failures: Other Subsystems	Total Failure Probability
Cryogenic Engines (H_2/O_2) - 357	10-40	60-90	0.028
Other Engines - 1310	40	60	0.008

<u>2/3 of liquid propulsion failures occurred in subsystems other than the engine</u>

PROPULSION SUBSYSTEM DEFINITIONS
FOR
ENGINE OUT CAPABILITIES

Analysis of propulsion subsystem reliability with engine out capability requires segregating the propulsion subsystem into two major segments. The first is an engine segment, which includes all ancillary components which support a single engine and which can be isolated (shutdown) from the rest of the subsystem in the event of an non-catastrophic anomaly associated with that engine. The second is the stage level segment which includes components of the propulsion subsystem supporting a cluster of engine segments and for which failure will lead to total loss of propulsion capability.

PROPULSION SUBSYSTEM DEFINITIONS FOR ENGINE-OUT CAPABILITY

	Subsystem Components
Engine Segment Subsystems (associated with an engine)	
o Engine	Engine, engine control electronics
o Other Subsystems associated with a particular engine	
/ Thrust vector control	Actuators, hydraulic pumps, gimbals, interface electronics
/ Propellant feed	Feed lines, valves, flex joints
Stage Level Subsystems (all subsystems which support more than one engine)	
o Engine Cluster Control	Executive level engine out control
o Propellant tanks	Propellant tanks and associated feed lines, pre-valves, fill/drain
o Pneumatic	Tank pressurization, tank vent, He purge

CRITICAL PROPULSION SYSTEM FAILURE PROBABILITIES FOR SYSTEMS WITH ENGINE SEGMENT-OUT CAPABILITIES

To perform a failure probability analysis of a propulsion system comprised of a cluster of engines with an engine segment-out capability, a minimum of three failure probabilities must be identified and quantified. They are engine segment non-catastrophic failure probability, engine segment catastrophic failure probability, and stage failure probability. Their definitions are presented on this chart. With these critical parameters defined, the flight failure histories were revisited to categorize each of the failures into one of the three types of failures.

The next chart presents a listing of the failures and their categorization.

CRITICAL PROPULSION SYSTEM FAILURE PROBABILITIES FOR SYSTEMS WITH ENGINE SEGMENT-OUT CAPABILITIES

- Engine Segment Non-Catastrophic Failure Probability (NFP) - The probability that an engine segment will shutdown in flight without causing the failure of other flight critical elements.

- Engine Segment Catastrophic Failure Probability (CFP) - The probability that an engine segment will fail catastrophically in flight, thereby causing the vehicle to fail.

- Stage (Catastrophic) Failure Probability (SFP) - The probability that a catastrophic failure will occur in a propulsion subsystem at the vehicle stage level, thereby causing the vehicle to fail.

LIQUID PROPULSION FAILURE HISTORY
APPLICATION TO ENGINE SEGMENT-OUT CAPABILITIES

The U.S. engine flight history was analyzed with engineering judgments made for each failure as to the category, engine segment (ES) or stage level (SL), and whether in an engine segment-out system the failure would have been non-catastrophic or catastrophic. The results are shown on the accompanying chart. Note that two second burn failures for the RL-10 are applicable to upper stages only.

Examples of the engineering judgments applied to categorize a particular failure follow: 1) The RL10 LO_2 tank leak was categorized as a stage level failure which would have been catastrophic to the mission, even with an engine-out capability. This judgment was based upon the fact that propellant was lost due to the leak which prevented both RL-10 engines from igniting at the time a restart of the engine was required to complete the mission. 2) During a Saturn launch, an engine shutdown was followed by a second engine shutdown which was judged to be correlated with the first. This was, therefore, considered to be a failure at the stage level which could be catastrophic if the engine-out system were not capable of providing mission success with two engines shutdown. 3) Another example of the problem of correlated failures occurred on Shuttle flight 51F. Following the shutdown of one SSME, a second engine shutdown was prevented by manual override from the ground, thus avoiding a failure of the orbiter to abort to orbit.

The historical and postulated failure probabilities resulting from this analysis are presented on the next chart.

LIQUID PROPULSION FAILURE HISTORY
APPLICATION TO ENGINE OUT CAPABILITIES

VEHICLE	ENGINE	STAGE FLIGHTS	ENGINE FLIGHTS	DESCRIPTION	ENGINE SEGMENT OR STAGE LEVEL	NON-CATASTROPHIC W/ENGINE OUT?
CRYOGENIC ENGINES						
CENTAUR	RL-10	69 1)	138	LOSS OF C2 HYDRAULIC POWER - MECH. FAILURE AT TURBOPUMP	ES	Y
				LOSS OF H2O2 PRECLUDED SUCCESSFUL MES2 - LEAK IN RCS	N/A	N/S 2)
				MES2 NOT ACHIEVED - LO2 LEAK FREEZING H2O2 LINES	N/A	N/A 2)
				LO2 BOOST PUMP FAILED TO OPERATE FOR MES1	ES	Y
				LO2 TANK LEAK - ANOMALOUS SEPARATION & FIRST BURN	SL	N
SATURN I	RL-10	9	54	NO FAILURES		
SATURN V	J2	22 3)	87	INJECTOR BURN THROUGH - POSSIBLE FUEL LINE FAILURE 4)	ES	Y
				ERRONEOUS ELECTRICAL SIGNAL 4)	SL?	N?
				FUEL LINE FAILURE - LH2 LEAK IN ENGINE COMPARTMENT 4)	ES	Y?
				PREMATURE CUTOFF	ES	Y
SHUTTLE	SSME	26 / 126	78 / 357	TEMP. SENSOR - MANUAL OVERRIDE OF 2ND SHUTDOWN	ES	Y
NON-CRYOGENIC ENGINES						
ATLAS	MA-2/MA-3	101 5)	303	BOOSTER FUEL PRE-VALVE INADVERTENTLY CLOSED	ES	Y
				BOOSTER GENERATOR HOT GAS LEAK - ENGINE DUCTING CRACK	ES	N?
				BOOSTER LUBE OIL LOSS	ES	Y
				BOOSTER GAS GENERATOR FUEL COOLING PORTS CLOGGED	ES	Y
DELTA	RS-27/AJ-10	181	362	FIRST STAGE HYDRAULIC (GIMBAL) FAILURE	ES	Y
				SECOND STAGE HYDRAULIC (GIMBAL) FAILURE	ES	Y
SATURN I	H-1	19	133	TURBOPUMP FAILURE 4)	ES	Y?
SATURN V	F-1	13	65	NO FAILURES		
TITAN	LR-87/LR-91	149 / 463	447 / 1310	GROSS CONTAMINATION IN PROPELLANT LINE	SL?	Y
				TURBINE DRIVEN HYDRAULIC PUMP OVER PRESSURE	ES	Y
				MASSIVE OX LEAK	ES	N?

1) EXCLUDES NO TRIALS DUE TO LV FAILURE
2) FAILURE MODE NOT APPLICABLE TO LAUNCH VEHICLE
3) INCLUDES 9 SATURN IB (1 ENGINE PER LAUNCH)
4) MISSION SUCCESS OR PARTIAL SUCCESS BECAUSE OF ENGINE OUT CAPABILITY
5) ATLAS WITH CENTAUR ONLY PRIOR TO 5/75, ALL ATLAS LAUNCHES THEREAFTER

HISTORICAL FAILURE RATIOS AND POSTULATED PROPULSION FAILURE PROBABILITIES

This chart summarizes the historical failure ratios for both cryogenic and non-cryogenic propulsion systems and postulated failure ratios for cryogenic propulsion systems. The 0.008-0.016 failure ratio for cryogenic systems at the stage level is associated with the tank leak on a Centaur flight discussed previously plus the possibility that an electrical signal problem on Saturn V occured at the stage level. The engine segment historical catastrophic failure ratio of 0-0.003 for cryogenic system is associated with: 1) the lower bound of zero - no cryogenic engine segment was found to have failed catastrophically in flight - and 2) the upper limit of 0.003 - correlated shutdown of two engines on a Saturn flight as discussed previously.

The postulated failure ratios are based on incorporating improved technology, design and testing, including redundancy and reduced correlated failures at the propulsion stage level. Additionally, it should be possible to reduce non-catastrophic engine segment failures by implementing launch vehicle hold down on the pad during engine start-up before liftoff.

HISTORICAL FAILURE RATIOS AND POSTULATED PROPULSION FAILURE PROBABILITIES

	Per Stage	Per Engine Segment	
	Level	Catastrophic	Non-Catastrophic
Historical Failure Ratios			
Cryogenic Stages	0.008-0.016	0-0.003	0.014-0.020
Non-Cryogenic Stages	0-0.002	0-0.002	0.005-0.008
Postulated Cryogenic Stage Improvements	Redundancy and Reduced Correlated Failures		Vehicle Holddown
Failure Probabilities	0.001-0.002	0.001-0.002	0.007-0.014

LAUNCH VEHICLE SUBSYSTEM FAILURE DEFINITIONS

With the introduction of redundancy, performance margins and abort capability, non-catastrophic subsystem failure modes exist for which survival and even mission success are possible. From the launch vehicle standpoint, the term <u>non-catastrophic</u> subsystem failure is used within this report to distinguish potentially vehicle survivable failures from <u>catastrophic</u> failures for which vehicle loss is certain.

Non-catastrophic failure is most evident with premature engine segment shutdown. With sufficient performance margins and an adaptive system, shutdown effects can be largely mitigated.

LAUNCH VEHICLE SUBSYSTEM FAILURE DEFINITIONS

For the purposes of this study, the following subsystem failure definitions are used:

- Catastrophic subsystem failures are those which would lead to mission failure, payload loss and, for manned vehicles, Orbiter or manned vehicle loss

- Non-catastrophic subsystem failures are those which do not propagate to other subsystems and, therefore, may be countered with vehicle redundancy and margins, i.e., engine-out capability, with 3 possible consequences:

  / Mission Success
  / Vehicle Abort
  / Mission Failure[1)]

1) The Shuttle has an engine-out capability which results in the vehicle entering and abort mode (with only small probability of mission success)

LAUNCH VEHICLE SUBSYSTEM FAILURE RATIO
HISTORICAL AND POSTULATED

The two historical solid rocket motor failures of Shuttle and Titan can best be characterized as design and process failures, respectively. The .007 failure ratio shown reflects the Titan failure. Considering the recovery efforts on both programs, it is reasonable to expect an improvement constrained by the state-of-the-art in non-destructive testing.

There is no evidence of a catastrophic cryogenic engine failure in U.S. flight history. However, their was a case of two correlated engine failures in a Saturn flight, yielding a failure ratio of .003 and a postulated mean value of 0.0015. This is about a factor of two lower than the estimated criticality one failure probability for the SSME derived recently from ground test data.

Projections for stage level failure ratios for cryogenic systems were tempered by the lower historical rate achieved with non-cryogenic systems. Additionally, a substantial reduction in stage level failure rates was postulated for Shuttle and any new system with high redundancy.

The other (non-propulsion) subsystem failure history involves single string guidance, power, RCS and other subsystems typical of expendable launch vehicles. Redundancy and multiple string voting should provide a substantial improvement.

With respect to non-catastrophic failures, vehicle hold-down did not apply to all of the data base. Since it does apply to all vehicles considered here, a modest improvement is postulated.

The data base for other subsystem non-catastrophic failure ratios generally applies to non-redundant systems. A factor of two reduction should be achievable with redundancy.

LAUNCH VEHICLE SUBSYSTEM FAILURE RATIO PROJECTIONS HISTORICAL AND POSTULATED

Subsystem Failure	Historical: Data Base	Historical: Failure Ratios[1]	Improvements	Postulated: Failure Ratios[1] (Mean)	Postulated: Fraction of Historical
Catastrophic					
Solid Propulsion	Titan	.007	Improved design/ processing	.003-.006 (.0045)	0.64
Cryogenic Propulsion Engine Segment	J2/RL10/ SSME	0-.003	Reduced correlated failures	.001-.002 (.0015)	1.00
Stage Level	"	.008-.016	Redundancy	.001-.002 (.0015)	0.13
Other	Titan/ Delta/Centaur	.004-.009	Guidance Redundancy	0-.002 (.001)	0.15
Non-Catastrophic					
Cryogenic Propulsion Engine Segment	J2/RL10/ SSME	.014-.020	Vehicle hold-down	.007-.014 (.0105)	0.62
Other[2]	Delta/Titan	0-.022	Redundancy	.003-.007 (.005)	0.45

1) Per unit
2) Non propulsive subsystems

MAIN PROPULSION FAILURE PROBABILITY
3 ENGINE CRYOGENIC STAGE

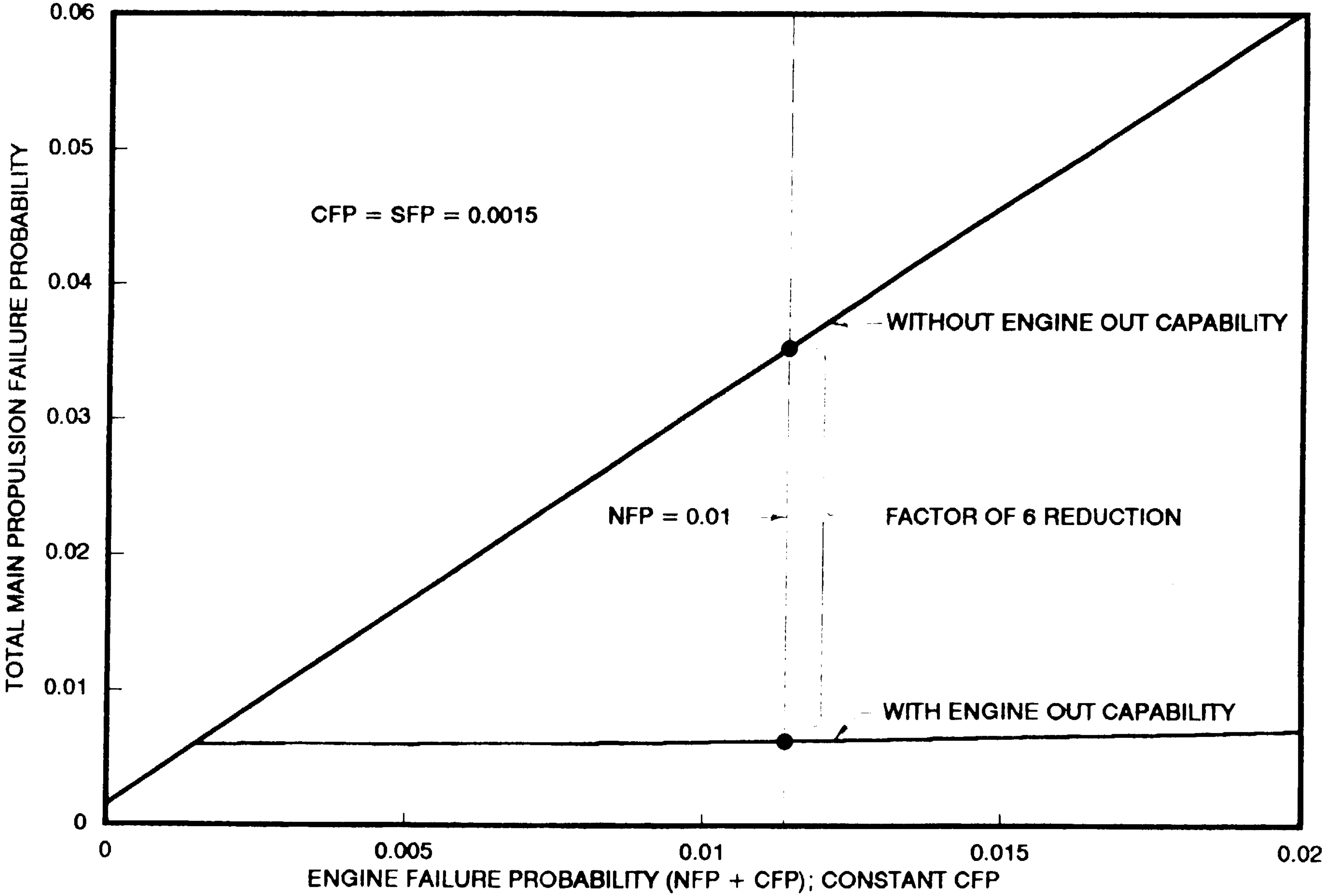
Current unmanned launch vehicles are subject to mission failure due to any failure, catastrophic or non-catastrophic. Because propulsion systems are the largest contributors to vehicle failures, considerable attention is being given to engine segment-out capabilities in future launch vehicles.

This chart presents failure probabilities for the main (liquid) propulsion system for a vehicle stage with three cryogenic engines, with and without engine segment-out capability plotted against engine failure probability (NFP + CFP). The mean values for the failure probabilities, CFP, and SFP discussed earlier were used in the analysis. The total engine failure probability, NFP + CFP, was allowed to vary by varying NFP. The value of the total for which NFP is 0.01, as discussed earlier, is highlighted.

The results indicate that, for NFP = 0.01, the propulsion failure probability for the stage would be expected to be reduced by a factor of 6 with engine segment-out from liftoff as compared to no engine segment-out capability. (The term "engine-out" capability is generally used for engine segment-out capability.) With engine-out capability, the total propulsion system failure probability is driven almost entirely by the catastrophic engine segment failure probability. To a good approximation, the total catastrophic failure probability is equal to the sum of the SFP and the product of the CFP and the number of engines.

MAIN PROPULSION FAILURE PROBABILITY

3 ENGINE CRYOGENIC STAGE



UNMANNED LAUNCH VEHICLE
ASCENT MISSION PROBABILITIES

For very low subsystem failure probabilities, it can be shown that a good approximation of the <u>system</u> failure probability is simply the sum of the <u>subsystem</u> failure probabilities. Thus, the postulated subsystem mean value probabilities from a previous chart can be used to project the mission failure probabilities for the unmanned vehicles as shown on this chart. The differences for the vehicles are due to differences in engine segment-out capabilities. Specifically, the non-catastrophic engine system failure probability for SHC2 (0.01 per engine) equals 0.02. For the SHC3/ILV with capability to achieve mission orbit with one engine segment-out, the failure probability for that case, by definition, is zero. The probability for two or more non-catastrophic engine segment failures is near zero for all of the vehicles.

The probabilities of payload loss and mission success are approximately 0.04 and .96, respectively for the SHC2. The corresponding probabilities for SHC3/ILV are 0.02 and 0.98.

UNMANNED LAUNCH VEHICLE
ASCENT MISSION PROBABILITIES

Launch Vehicle Ascent Event	Mean Failure Ratio per unit	No. of Units	SHC2	No. of Units	SHC3/ILV
Catastrophic Failure					
Solid Propulsion	.0045	2	.009	2	.009
Cryogenic Propulsion					
Engine Segment	.0015	2	.003	3	.0045
Stage Level	.0015	1	.0015	1	.0015
Other	.001	1	.001	1	.001
Non-Catastrophic Failure					
1 Engine-out	.0105	2	.020	-	0[1]
>1 Engine-out			.0001	-	.0004
Other	.005	1	.005	1	.005
Mission Failure (Payload Loss)			.040		.021
Mission Success			.960		.979

[1] With an engine-out capability, from liftoff, to reach mission orbit, that event is no longer in the category of a mission critical failure

MANNED LAUNCH VEHICLE OPERATIONS EVENT TREE

While a traditional, single string rocket can be evaluated on a simple payload loss/mission success basis using vehicle failure probability, introduction of partial to full engine-out capability, abort capability and on-orbit and reentry/landing sequences requires a more complex analysis of flight event probabilities and alternative consequences. Accordingly, it is useful to organize the flight phases for Shuttle, manned SHC and manned ILV into a tree where the particular branch followed on any given flight depends on the events (success or the specific type of failure) occurring in the prior flight phase.

Probabilities within the tree are determined as follows:

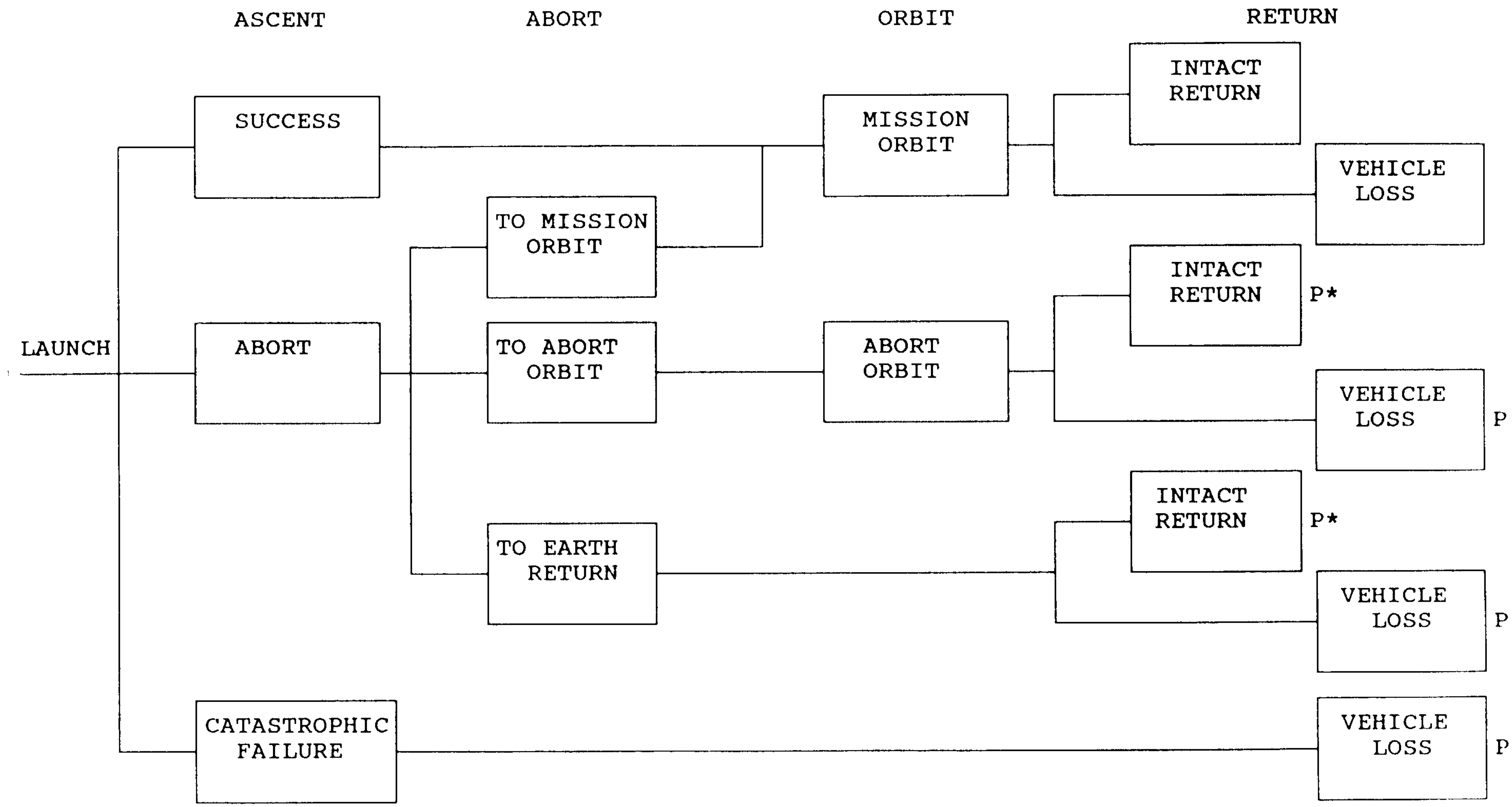
The total probability of a particular event
equals
The probability of entering the flight phase due to prior events
times
The probability of the event assuming entry into that flight phase

In the following charts, flight event probabilities are developed by flight phase and accumulated to determine total probabilities of successful mission, payload loss and manned vehicle loss on a per launch basis. (The event/consequence tree is duplicated in Monte Carlo simulation models using input values to analyze availability and additional issues. In the Monte Carlo analyses, probability ranges with triangular distributions were used rather than mean values.)

A more detailed discussion of the tree and its branches will be given as the probabilities of the events are developed.

MANNED LAUNCH VEHICLE OPERATIONS EVENT TREE

SHUTTLE/SHC3 OR ILV



PAYLOAD LOSS (P/P+P*)

ASSUMED ABORT CAPABILITIES FOR MANNED LAUNCH VEHICLES

In the event of a non-catastrophic shutdown of an SSME, the Shuttle enters an abort mode. The specific abort mode selected depends on the time after launch. For a future manned launch vehicle, either the SHC3 or an ILV, it is assumed that the vehicle will have the capability to place the manned vehicle in its mission orbit with one non-catastrophic engine shutdown having occurred at any time after liftoff.

Other non-catastrophic vehicle failures, being varied in nature and time of occurrence, are assumed to cause any of the vehicles to enter the abort mode.

ASSUMED ABORT CAPABILITIES FOR MANNED LAUNCH VEHICLES

- o One Engine Segment Non-Catastrophic Failure
  - / Shuttle enters an abort mode
  - / SHC3 or ILV continues to mission orbit[1)]
- o Other non-catastrophic failures cause all manned vehicles to enter the abort mode
- o For SHC3 and ILV aborts to abort orbit and Earth, the payload is lost

1) i.e. SHC3 and ILV are assumed to have an engine segment-out capability, from liftoff, to complete the mission.

MANNED LAUNCH VEHICLE ASCENT PHASE MISSION PROBABILITIES

Considering the subsystem failure probabilities of the vehicles analyzed, the essential differences in their operational capabilities lies in the differences in their engine segment-out capabilities. Specifically, for those vehicles having an engine-out capability, from liftoff, to perform the mission, the consequence of a non-catastrophic failure would not be an "abort" mode, i.e., the event would become an in-flight anomoly because the performance margin of the vehicle would assure a "normal" trajectory. Accordingly, the assumed probability of achieving mission success without entering the abort mode is significantly different for Shuttle and the postulated future manned launch vehicles.

MANNED LAUNCH VEHICLE ASCENT PHASE PROBABILITIES

Launch Vehicle Event	Mean Failure Ratio per unit	Number of units	Shuttle	SHC3/ILV
Catastrophic Failure				
Solid Propulsion	.0045	2	.009	.009
Cryogenic Propulsion				
Engine Segment	.0015	3	.0045	.0045
Stage Level	.0015	1	.0015	.0015
Other	.001	1	.001	.001
Catastrophic Failure			.016	.016
Non-Catastrophic Failure				
1 Engine-out	.0105	3	.031	0[1]
>1 Engine-out			.0004	.0004
Other	.005	1	.005	.005
Enter abort mode			.036	.005
Direct Ascent Mission Success (without abort)			.948	.979

[1] With an engine-out capablity, from liftoff, to reach mission orbit, that event is no longer in the category of a mission critical failure.

SHUTTLE/SHC3/ILV MANNED VEHICLE ABORT FREQUENCIES

The probabilities of entering the abort mode during ascent are about a factor of seven lower for SHC3/ILV as compared to the Shuttle. This is due to the assumption that future U.S. manned launch vehicles will have a full engine segment-out capability, from liftoff, to perform the mission. Correspondingly, the expected numbers of launches and time intervals between aborts are projected to be a factor of seven greater.

SHUTTLE/SHC3/ILV MANNED VEHICLE ABORT FREQUENCIES

	Shuttle	SHC3/ILV
Probability of entering the abort mode	.036	.005
Expected number of launches between aborts	**28**	**200**
Expected number of years between aborts (14 launches/year)	2	14

ONE ENGINE-OUT ABORT OPTIONS/CAPABILITIES

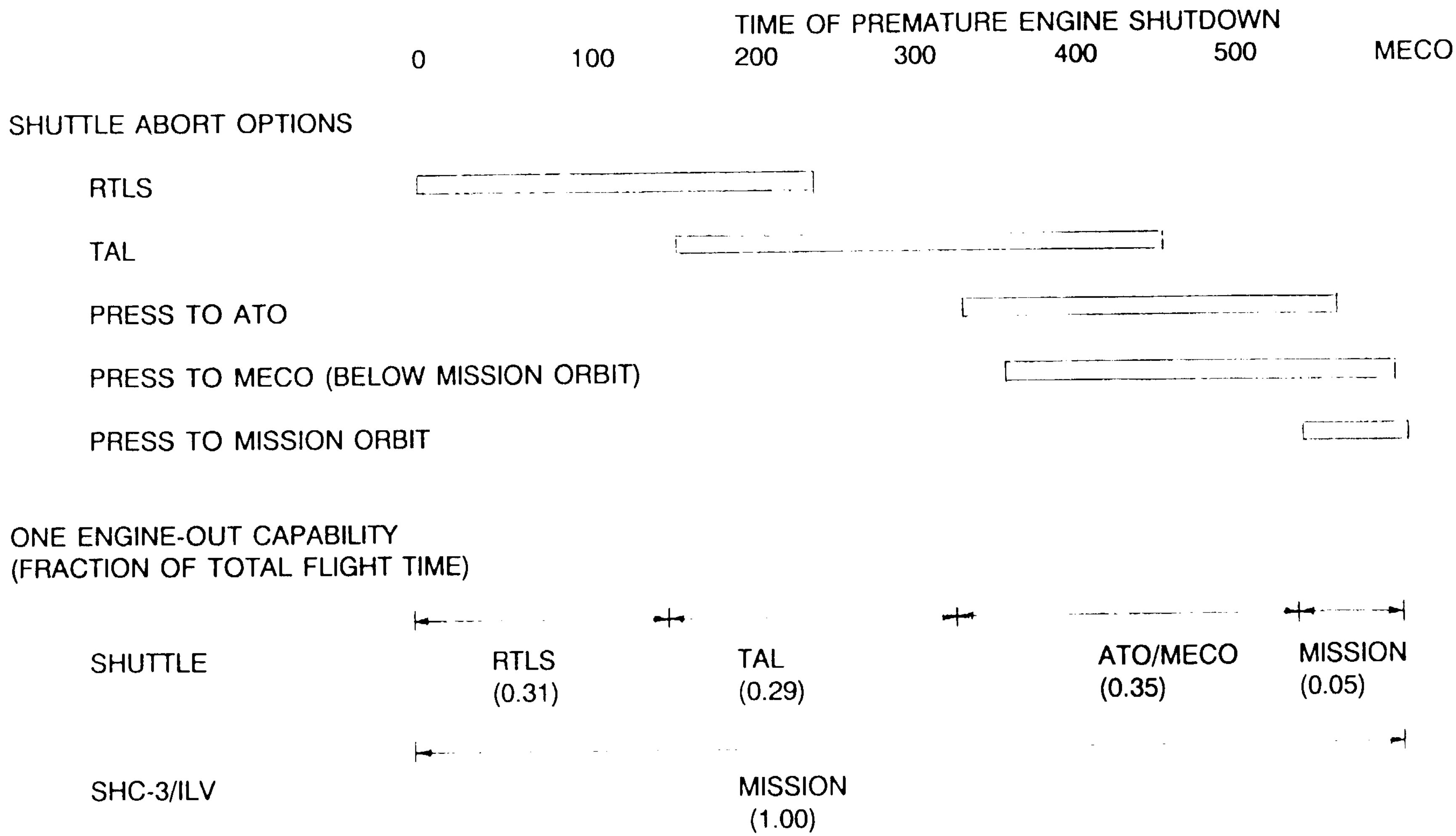
The upper portion of this chart shows the windows for the various Shuttle abort modes during ascent. Several observations about aborts can be made. Trans-Atlantic Landing (TAL) abort windows begin to open at about 160 seconds. Thus, before that time only the Return To Launch Site (RTLS) mode is available (about 31% of the ascent time). Abort to orbit is achievable for the last 40% of the mission ascent time, and an abort to the mission orbit is achievable for only the last 5% of the ascent time.

By design definition, the manned launch vehicles with the capability to achieve mission orbit with one engine segment-out from liftoff would not enter abort modes under those circumstances.

Review of SSME test history reveals a cluster of engine non-catastrophic shutdowns in the first few seconds of engine burn. However, because of the 6.6 sec SSME start up on the pad, failures for this analysis are assumed equally probable at any time during flight. Thus, the fraction of time an abort option is available represents the probability of that abort mode occurring if an engine shutdown occurs.

Accordingly, the probabilities of Shuttle entering the abort to earth, to abort orbit and to mission orbit are assumed to be 0.6, 0.35 and 0.05, respectively. Given a lack of time-of-failure data, these probabilities are assumed to apply to "other" subsystem non-catastrophic failures also. For SHC3 and ILV, the time of one-engine shutdown is not applicable because performance margin assures achieving mission orbit.

ONE ENGINE-OUT ABORT OPTIONS/CAPABILITIES



SHUTTLE ABORT/ORBIT/REENTRY FAILURE PROBABILITY ASSUMPTIONS

ONE ENGINE-OUT

Shuttle abort capabilities for Return To Launch Site (RTLS) and Trans-Atlantic Landing (TAL) and Abort To Orbit (ATO) have been certified by analysis in the event of one engine shutdown. As shown earlier, the probability of two engines-out is very small provided the probability of correlated engine shutdowns is low. Thus, the probability of abort failure following the two engine-out failure modes is not significant to the analysis. For the single engine-out case, RTLS and TAL are assumed to have a combined vehicle loss probability of 0.05, a factor of 10 greater than normal flight.

In the case of ATO, it is assumed that there is a probability of success of 1.0 when a non-catastrophic failure occurs after the abort to orbit windows have opened. Overall, it is expected that the probability assumptions for abort events lead to optimistic predictions for success.

For the orbit/reentry phase of the mission, the probability of Orbiter or manned vehicle loss is assumed to be 0.005. Lacking a design concept for a manned vehicle to be launched on SHC3/ILV, it is not possible to make assumptions different from those for Shuttle.

SHUTTLE ABORT/ORBIT/REENTRY FAILURE PROBABILITY ASSUMPTIONS

ONE ENGINE-OUT

Flight Phase	Certified Capability?	Postulated Loss Probability
RTLS/TAL	yes	.05
ATO	yes	0
Reentry from ATO	yes	.005

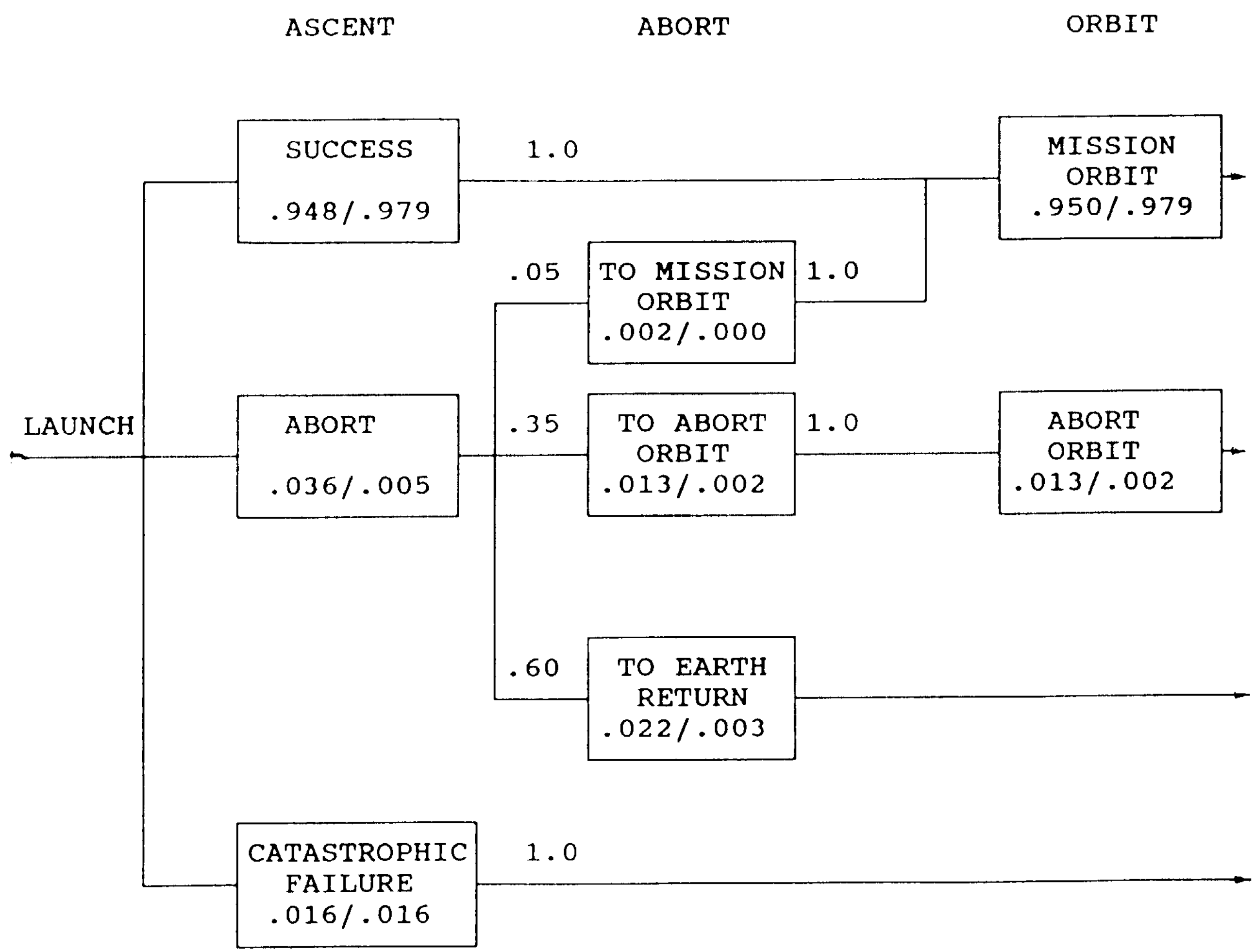
POSTULATED EVENT PROBABILITIES FOR ASCENT TO ORBIT PHASE
SHUTTLE/SHC3 OR ILV

Shown on this chart are the critical probabilities for ascent to orbit and the associated abort modes.

The contributions of the abort mode to achieving mission orbit are very small for the Shuttle, 0.002, and essentially zero for the SHC3 or ILV. Thus, the projected probabilities of mission success are 0.95 and 0.979 for the Shuttle and the SHC3 or ILV respectively, the essential differences being due to the differences in the assumed engine segment-out capabilities.

The abort-to-abort orbit and return-to-Earth modes will be presented on the next chart along with the orbit/reentry phase.

POSTULATED EVENT PROBABILITIES FOR ASCENT TO ORBIT PHASE
SHUTTLE/SHC3 OR ILV



SUCCESSFUL MISSION .950/.979
UNSUCCESFUL MISSION .050/.021

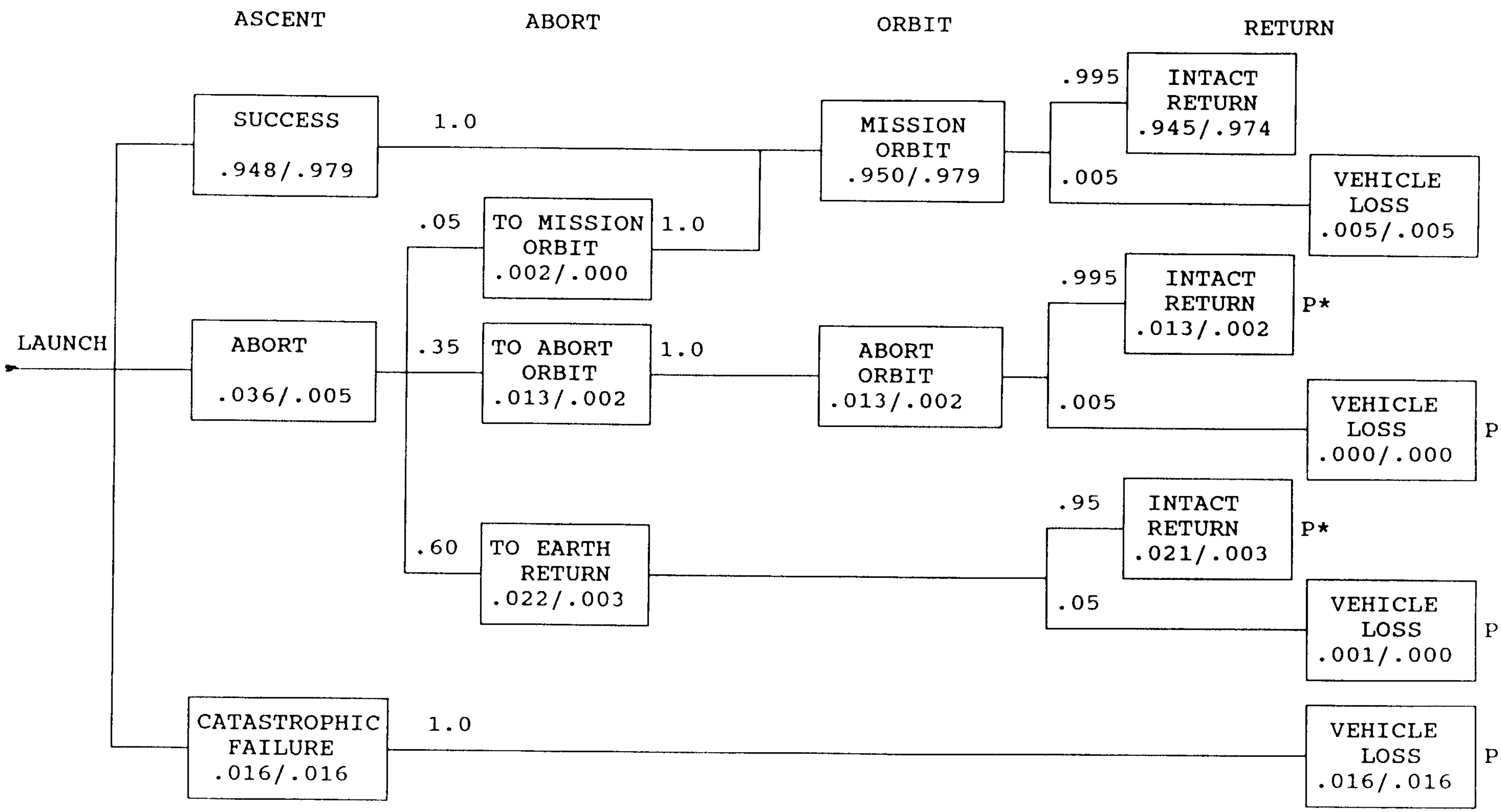
POSTULATE PROBABILITIES FOR ABORT MODES AND ORBIT/REENTRY PHASE
SHUTTLE/SHC3 OR ILV

The differences in operation probabilities shown on this chart also result from the assumed differences in one engine segment-out capabilities of the vehicles. The significant difference is the projected probabilities of the vehicles entering the abort mode, 0.036 for Shuttle and 0.005 for SHC3 or ILV. Lacking data on the design of the new manned vehicles, it was assumed that the probabilities of 1) entering the Abort-To-Orbit and Return-To-Earth modes, and 2) for abort success would be the same for all of the vehicles.

The probabilities of payload loss in the abort modes are different for Shuttle and SHC 3 or ILV in that the Shuttle has the capability to recover the payload in a successful abort, whereas for the latter systems only the manned vehicle is recovered.

A summary of mission success, payload loss and Orbiter/manned vehicle loss is presented on the next chart.

POSTULATE PROBABILITIES FOR ABORT MODES AND ORBIT/REENTRY PHASE
SHUTTLE/SHC3 OR ILV



SUCCESSFUL MISSION .950/.979 VEHICLE LOSS .022/.021
UNSUCCESFUL MISSION .050/.021 PAYLOAD LOSS (P/P+P*) .017/.021

SUMMARY OF MANNED VEHICLE OPERATION PARAMETERS
PROBABILITY/EXPECTED NUMER OF LAUNCHES BETWEEN FAILURES

The probabilities of mission success for Shuttle and SHC 3 or ILV are 0.950 and 0.979, respectively, with corresponding expected numbers of launches between failures of 20 and 48. The higher values for the new vehicles are a result of their assumed capabilities to achieve mission orbit with an engine segment-out discussed on previous charts.

The lower value for probability of payload loss for Shuttle are due to the capabilities of Shuttle to return a payload to Earth, not assumed for the new vehicles.

The Orbiter/manned vehicle loss probabilties are virtually the same for all vehicles in spite of the higher probability of the Shuttle entering the abort mode. This is due to the high success probability projected for the Shuttle in the abort mode which leads to Orbiter recovery. The cost of loss differs dramatically - approximately $2.5 billion for an Orbiter vis-a-vis a much lower cost for a manned vehicle.

SUMMARY OF MANNED VEHICLE OPERATION PARAMETERS
PROBABILITY/EXPECTED NUMBER OF LAUNCHES BETWEEN FAILURES

	Mission Success	Payload Loss	Orbiter/Manned Vehicle Loss
Shuttle	.950/20	.017/59	.022/45
SHC3 or ILV	.979/48	.021/48	.021/48

- o SHC3 and ILV with engine-out capability from liftoff more than doubles the expected launches between unsuccessful missions.
- o Shuttle abort effectiveness translates into lower payload loss frequency.
- o Although frequencies of manned vehicle loss are similar for Shuttle and SHC3/ILV, the costs of loss are dramatically different.

ADDITIONAL FACTORS AFFECTING EVENT PROBABILITIES

There are at least two factors which may affect the projected success and loss probabilities presented herein.

The analysis assumed uniform probability of ascent non-catastrophic failures, i.e., that failure would be equally probable at any time during flight. Analysis of SSME ground tests and flight history suggest that failures may occur non-uniformly with high probability that failures will occur within the first 10 seconds. While solid motor ignition is not initiated until 6.6 seconds after SSME start, there may be a residual bias toward early failures which would increase the probabilities of RTLS and TAL vis-a-vis those for ATO or achieving the mission orbit. Because RTLS and TAL are likely riskier abort modes, such a bias would increase the probability of orbiter loss.

Catastrophic failure implies catastrophic vehicle loss. With a small manned capsule or similar vehicle using an Apollo-like rocket escape system, it is conceivable that the vehicle could be ejected from the launch vehicle upon detection of a critical failure, increasing the probability of surviving a launch vehicle catastrophic failure. Indeed, the Soviets were able to recover a Soyuz capsule from a vehicle explosion and fire with a rocket escape system.

ADDITIONAL FACTORS AFFECTING EVENT PROBABILITIES

- o Time Distirbution of Non-Catastrophic Failures
  - / Analysis of SSME test and flight history suggests failures may occur early in flight rather than uniformly
  - / A bias toward early failures would increase the probability of RTLS and TAL vis-a-vis ATO, increasing the probability of orbiter loss
- o Escape from Catastrophic Failure
  - / A new manned vehicle with an Apollo-like escape system could reduce the probability of manned vehicle loss due to catastrophic failure
  - / A Soyuz crew escaped from an on-pad vehicle explosion and fire with such an escape system.

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SPACE STATION ERA MISSION MODELS

20/13 ASSEMBLY SEQUENCE
8/88 ALLOCATED ASSEMBLY WEIGHTS
SCHEDULED LOGISTICS AND PDRD PAYLOAD ALLOCATION

The NASA plan for deployment of the space station by the Shuttle, shown on this chart, was used to define the Shuttle Only mission model shown on a subsequent chart. The sequence includes three logistics flights.

20/13 ASSEMBLY SEQUENCE
8/88 ALLOCATED ASSEMBLY WEIGHTS
SCHEDULED LOGISTICS AND PDRD PAYLOAD ALLOCATION

1	FEL	MB-1	18.75 STBD PV MODULE, ALPHA JOINT, STBD TRUSS (2 BAYS), AVIONICS PALLET, ANTENNA PALLET, TANK FARM #3, RCS MODULES (2), AWP W/MOBILE TRANSPORTER
2		MB-2	STBD TRUSS (6 BAYS), STBD TCS SYSTEM, FTS/SHELTER, CMG PALLET, TANK FARM #1 (W/WEU),PMAD PALLET, TDRSS ANTENNA, RCS MODULE
3		MB-3	AFT STBD NODE, MODULE SUPPORT STRUCT, MSC PHASE 1, PRESS. DOCKING MODULE, FMAD PALLET, STINGER/RESISTORJET
4	EMTC	MB-4	U.S. LAB MODULE
5		MB-5	18.75 PORT PV MODULE, ALPHA JOINT, PORT TRUSS, TANK FARM #2 (W/WEU), RCS MODULE, PORT ANTENNA PALLET, UNPRESS. LOG. BERTHING MECH.
6		OF-1	PRESS. LOG. MOD., MODULE OUTFITTING
7		UOF-1	EXTENDED DURATION ORBITER (EDO), ATTACHED PAYLOADS & EQUIP.
8		MB-6	AFT PORT NODE, AIRLOCK (SSEMU VERF. UNIT/SSEMU), PRESS. DOCKING MODULE, ATTACHED PAYLOADS & EQUIP.
9		MB-7	U.S. HAB MODULE
10		MB-8	PORT & STBD FORWARD NODES, CUPOLA, MODULE OUTFITTING
11		MB-9	AIRLOCK (3 SSEMU), PORT TCS SYTEM, TANK FARM #4, CUPOLA, ATTACHED PAYLAODS & EQUIP.
12		OF-2	PRESS. LOG. MOD., MODULE OUTFITTING, SPDM, 2nd TRUSS UTILITIES
13	PMC	MB-10*	CREW (4), PRESS. LOG. MOD., UNPRESS. LOG. CARRIER, LOGISTICS
14		MB-11	PORT & STBD OUTBOARD PV MODULES (37.5 KW)
15		MB-12	SSRMS-2, MMD PHASE 1, ATTACH PAYLOADS & EQUIP., LOGISTIC SPARES
16		L-1*	PRESS. LOG. MOD., UNPRESS. LOG. CARRIER, LOGISTICS
17		MB-13	JEMMODULE, JEM EXPOSED FACILITY #1, LOGISTIC SPARES
18		MB-14	ESA MODULE, LOGISTIC SPARES
19		L-2*	PRESS. LOG. MOD., UNPRESS. LOG. CARRIER, LOGISTICS
20	AC	MB-15	JEM EXPOSED FACILITY #2, JEM ELM, INTL EQUIPMENT & PAYLOADS, LOGISTIC SPARES

*LOGISTICS FLIGHTS

SPACE STATION ASSEMBLY
EARLY MAN-TENDED CAPABILITY
STS & SHUTTLE-C
OMV GROUND BASED

A representative NASA plan for deployment of the Space Station with Shuttle and SHC is shown on this chart. On the basis of this plan, the total number of flights required, including initial logistic flights, would be reduced from twenty (for Shuttle Only) to thirteen. Shuttle and the SHC launch requirements would be nine and four, respectively, including two logistics flights.

SPACE STATION ASSEMBLY
EARLY MAN-TENDED CAPABILITY
STS & SHUTTLE-C
OMV GROUND BASED

FLIGHT	MANIFEST	FUNCTIONALITY	MASS/SH-C LENGTH**
STS 1*	P.V. MODULE, JOINT, TRUSS & UTIL, TANK FARM & ELECTROLYSIS RCS, ANTENNAS, DOCKING ADAPTER, AVIONICS PALLET, ERECTOR SET	FUNCTIONAL SPACECRAFT, 18.75 kW ARRAY 5 kW AVAIL) CONTROL PROVIDED BY PALLET	35667 (SST CAPABILITY 40530 TO 220)
STS 2*	NODE, TCS, FTS, DOCKING ADAPTER, CMG'S, TDRSS ANTENNA, TANK FARM, STINGER/RESISTOJET	SYSTEM FUNCTIONS PROVIDED BY NODE, TCS BY CENTRAL RADIATOR, CMG CONTROL	32664 (STS CAPABILITY 39530 TO 220)
SHC 1	LAB MODULE, NODE, SSRMS-2, OMV		93317/73*
STS 3	MSC PHASE 1, TANK FARM, DOCKING ADAP., AIRLOCKS(2), FMAD PALLET, RADIATOR PANELS	LAB MODULE OPERATIONAL (MAN-TENDED), SERVICING, STARBOARD RADIATOR, AIRLOCKS 18.75 kW	32266 (STS CAPABILITY 39530)
MAN TENDED (LAB FULLY OUTFITTED			
STS 4	P.V. MODULE, JOINT, TRUSS, RCS, TANK FARM, TCS, SSEMU	37.5 kW, TRUSS COMPLETE, PROPULSION SYSTEM COMPLETE	33524 (STS CAPABILITY 39530)
SH C-2	HAB MODULE, ATTACHED PAYLOADS, OMV		80381/71*
STS 5	NODES (2), CUPOLAS, EVA EQUIP.	HABITABILITY PROVISIONS, PAYLOADS	26882 (STS CAPABILITY 39530)
MODULE C/O			
PMC			
STS-6	CREW, LOGISTICS, SSEMUs	MANNED	36547 (190 N.M.) (STS CAPABILITY 42530)
SH C-3	OUTBOARD P.V.(2) & TRUSS, SPDM, SSEMU, JEM, OMV	75 kW, JEM	91455/66*
STS 7	LOGISTICS RESUPPLY, CREW		
SH C 4	JEM E.F.1, ATTACHED PAYLOADS, ESA MODULE, MMD, OMV	ESA, PAYLOADS, MMD	81900/81*
STS-8	LOGISTICS RESUPPLY, CREW		
STS-9	JEM E.F.2, ELM		36330 (190 N.M.) (STS CAPABILITY 42530)
PHASE I			

JS288132

*SAME AS BASELINE **MASS INCLUDES FSE

L. SYSTEMS, INC.

SPACE STATION ERA MISSION MODEL
SHUTTLE ONLY

The mission model for Shuttle only is based upon an assumption of fourteen planned Shuttle launches per year throughout the period of interest. Over and above the Space Station deployment and support launch requirements, about two per year were assigned to DoD launches. The remainder of the shuttle flight rate capabilities were assumed dedicated to pallet/manned and upper stage free flyer missions. The key assumptions for the mission model are the fourteen per year capability of the Shuttle and the launch rate requirements for deployment of the Station. The results of this study are not sensitive to the distribution of the "other" launches among other users.

The major risk of particular concern to the Space Station deployment is loss of a module. The risks to all space programs supported by the Shuttle are its launch availability and the possible loss of one or more Orbiters.

SPACE STATION ERA MISSION MODEL

SHUTTLE ONLY

MISSION GROUP	YEAR					RISK ISSUE
	1	2	3	4	5	
SPACE STATION						
DEPLOY	5	6	6	0	0	PROB. OF STATION MODULE LOSS
SUPPORT	0	0	3	5	5	AVAILABILITY (STATION EMERGENCY)
DOD	2	2	2	2	2	AVAILABILITY (NATIONAL PRIORITY)
PALLET/MANNED	5	4	1	1	1	
U/S /FREE FLYERS	2	2	2	6	6	AVAILABILITY (PLANETARY WINDOW)
TOTAL	**14**	**14**	**14**	**14**	**14**	PROB. OF ORBITER LOSS

MISSION FLIGHT ASSIGNMENTS WITH AN UNMANNED SHC/ILV

Introduction of an unmanned SHC or ILV would permit shuttle off-loading of certain Space Station modules and other unmanned cargo (such as free flyer observatories and upper stages). The off-loading was limited to constrain the SHC launch rate to 3 launches per year, determined by the availability of SSMEs. Although an ILV could potentially carry more of the Shuttle traffic, SHC rates were assumed for comparison purposes.

MISSION FLIGHT ASSIGNMENTS
WITH AN UNMANNED SHC/ILV

MISSION GROUP	YEAR 1	2	3	4	5
Space Station					
Deploy					
Shuttle	4	3	0	0	0
SHC/ILV	1	2	1	0	0
Support					
Shuttle	0	0	5	5	5
DoD					
Shuttle	1	1	1	1	1
SHC/ILV	1	1	1	1	1
Pallet/Manned					
Shuttle	5	4	1	1	1
U/S /Free Flyers					
Shuttle	0	2	0	0	0
SHC/ILV	1	0	1	3	3
Shuttle Total	**10**	**10**	**7**	**7**	**7**
SHC/ILV Total	**3**	**3**	**3**	**4**	**4**
TOTAL	**13**	**13**	**10**	**11**	**11**

MISSION FLIGHT ASSIGNMENTS
WITH MANNED AND UNMANNED SHC/ILV LAUNCHES

Introduction of a SHC3/ILV with both manned and unmanned capabilities could be phased to achieve the Space Station deployment with the Shuttle and unmanned launches of the SHC3/ILV. Thereafter, the manned SHC3/ILV would provide crew rotation and emergency escape for the Space Station. This would serve to reduce Shuttle launches to those requiring the unique on-orbit capabilities of the Orbiter. Shuttle flight rates in the out years were reduced to 3 per year to envelope the effects of this scenario.

MISSION FLIGHT ASSIGNMENTS
WITH MANNED AND UNMANNED SHC/ILV LAUNCHES

MISSION GROUP	YEAR 1	2	3	4	5	SHC/ILV MODE
Space Station						
Deploy						
Shuttle	4	3	0	0	0	
SHC/ILV	1	2	1	0	0	Unmanned
Support						
Shuttle	0	0	1	1	1	
SHC3/ILV			4	4	4	Manned
DoD						
Shuttle	1	1	1	1	1	
SHC/ILV	1	1	1	1	1	Unmanned
Pallet/Manned						
Shuttle	5	4	1	1	1	
U/S /Free Flyers						
Shuttle	0	2	0	0	0	
SHC/ILV	1	0	1	3	3	
Shuttle Total	**10**	**8**	**3**	**3**	**3**	Unmanned
SHC/ILV Total	**3**	**3**	**7**	**8**	**8**	
TOTAL	**13**	**13**	**10**	**11**	**11**	

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SPACE TRANSPORTATION SYSTEMS OPERABILITY ANALYSES

U.S. LAUNCH VEHICLE HISTORY AND PROJECTIONS OF DOWNTIMES

Launch fleet operations analyses require postulated downtimes when a vehicle fails. Accordingly, in addition to failure ratios, the history of launch vehicle downtimes after a failure, was analyzed. As in the case of failure ratios, downtimes can be associated with particular subsystem failures. A summary of historical downtimes is shown here for the available data base which is largely for expendable, unmanned launch vehicles. The projected values are for future, high value space cargos such as manned vehicles and Space Station modules. They represent engineering judgments of the mean downtimes that will result from compromises between operational requirements and risks associated with the next launch after a launch failure has occurred.

U.S . LAUNCH VEHICLE HISTORY AND PROJECTIONS OF DOWNTIME

Failure Mode	Data Base	Historical Downtime (mos.)	Projected Downtime (mos.)
Solid Propulsion	Titan/ Shuttle	19-32	12
Catastrophic			12
Engine-out = 1	ELVs	3-8	3-12
> 1			6
Other	ELVs	2-6	3
Catastrophic Orbital, Reentry	-	-	16

RISK OF MANNED VEHICLE LOSS
FIVE YEAR MODEL

Using the event probabilities outlined earlier in the briefing and the five-year mission models, Monte Carlo simulations were performed for the various vehicle fleets to examine overall fleet operational risk.

This chart summarizes the expected number of Orbiter or manned vehicle losses during the five-year mission model period. For the Shuttle Only case, expected losses are slightly more than one Orbiter, i.e., the program should be planned on the basis of loss of at least one Orbiter in the course of operations during the five years, recognizing that there is a significant probability of greater or lower losses. Because the overall flight rates are relatively similar and the proportion of traffic assigned to the SHC or ILV is low, the overall risk of vehicle loss does not vary significantly among the cases. For the cases with an alternate manned vehicle, Orbiter losses remain relatively high as compared to the new manned vehicle because operations for the new manned vehicle do not begin until completion of Space Station deployment. If the mission model post-deployment flight rates were continued, one would expect the losses per flight for the two vehicles to be approximately equal (as shown earlier).

RISK OF MANNED VEHICLE LOSS
FIVE YEAR MODEL

	Expected Orbiter Losses	Expected Manned Vehicle Losses
Shuttle	1.1	-
Shuttle + SHC2	0.9	-
Shuttle + SHC3	0.8	-
Shuttle + ILV	0.8	-
Shuttle + Manned SHC3	0.6	0.2
Shuttle + Manned ILV	0.6	0.2

SPACE STATION DEPLOYMENT RISK
(SPACE STATION DEPLOYMENT LAUNCHES ONLY)

This chart focuses on impacts to the space station deployment activities. It is highly likely that Space Station deployment would be stretched out (or other programs would be delayed if Space Station had higher priority) due to aborts or other failures as is evidenced by comparing successful launches to manifested launches. The degree of stretch-out could be expected to be reduced with the availability of an unmanned SHC or ILV.

The results in the fourth column show that the chances of losing one or more Space Station modules vary from about 1 in 2 for the Shuttle Only to about 1 in 3 for the Shuttle plus SHC3 or ILV fleets.

The lower value for the SHC ILV cases should be tempered by the fact that they would carry the equivalent of two Shuttle flights worth of modules on any single flight, thus increasing the impact of loss should one occur.

SPACE STATION DEPLOYMENT RISKS
(SPACE STATION DEPLOYMENT LAUNCHES ONLY)

	PLANNED LAUNCHES	EXPECTED/0.9 PROB.[1] SUCCESSFUL LAUNCHES	PROB. OF ONE OR MORE LAUNCH FAILURES
SHUTTLE ONLY	17	15.6 / 12.8[1]	0.53
SHUTTLE + SHC2	11	10.5 / 7.9	0.44[2]
SHUTTLE + SHC3	11	10.7 / 8.4	0.37[2]
SHUTTLE + ILV	11	10.9 / 9.1	0.38[2]

1) 0.9 PROBABILITY OF N LAUNCHES OR GREATER
2) MULTIPLE SHUTTLE EQUIVALENT CARGO MANIFESTED ON SHC/ILV

LAUNCH VEHICLE RISKS PER LAUNCH

The critical operational parameters per launch are peculiar to the individual launch vehicles, independent of their operations in a mixed fleet. Although they are discussed earlier in the briefing, they are summarized here for all of the vehicles analyzed.

With respect to the probability of mission failure, the Shuttle is highest because when an engine segment fails non-catastrophically, it aborts. The SHC2 is next highest, event though it has no abort capability. This is because it has a lower total (non-catastrophic + catastrophic) failure probability than Shuttle due to having one less SSME. Vehicles which can achieve mission orbit with an engine segment out have the lowest mission failure probability.

The Shuttle has the lowest probability of payload loss because in a successful abort, the payload is saved in addition to the Orbiter.

Unlike the significant differences in the probabilities of unsuccessful mission, the Shuttle and SHC3/ILV probabilities of manned vehicle loss are about the same due to the high probabilities of successful Shuttle abort. The cost of loss differs, though - approximately $2.5 billion for an Orbiter versus a much lower cost for a smaller, less complex manned vehicle.

LAUNCH VEHICLE RISKS PER LAUNCH

	Probability of Unsuccessful Mission	Probability of Payload Loss	Probability of Orbiter/Manned Vehicle Loss
Shuttle	.05	.017	.022
SHC2	.04	.040	-
SHC3	.021	.021	-
ILV	.021	.021	-
Manned SHC3	.021	.021	.021
Manned ILV	.021	.021	.021

FLEET OPERATIONAL RISKS

Two measures of the viability of a launch fleet to meet a specified mission model are the relative values of planned launch rate versus the expected successful launch rate and the launch availabilities. The first effect of introducing a second vehicle to support the Shuttle is to reduce the planned launch rate due to manifesting of payloads on the higher performance second vehicle. This also reduces the differences between planned and successful launch rates, thus decreasing the risks of not meeting the mission model requirements. Also, the lower planned launch rates could probably be increased without exceeding the launch rate limitations of the facilities, further reducing the risks.

Projected fleet launch vehicle availabilities range from about 80% to 90%. The improvement in vehicle availability for cargo launch (unless dual compatible) with an ILV probably would not justify the additional development cost over that for SHC. For unmanned cargos which were dual compatible on Shuttle and an ILV, and for a manned vehicle launched on the ILV, the launch availability would be 98%. Thus, an independent manned capability complementing Shuttle, provides the greatest assured manned access capability. This would be particularly important in reducing the risks to manned safety and support of the Space Station.

FLEET OPERATIONAL RISKS

5 YEAR MODEL (SHUTTLE/SHC OR ILV)

	Expected				
	Planned Launches		Successful Launches		Vehicle Availability
	Vehicles	Total	Vehicles	Total	
Shuttle Only	70/-	70	46/-	46	0.79/-
Shuttle + SHC2	41/17	58	35/12	47	0.76/0.82
Shuttle + SHC3	41/17	58	34/14	48	0.77/0.80
Shuttle + ILV	41/17	58	37/16	53	0.81/0.90 (0.98)[1)]
Shuttle + Manned SHC3	29/29	58	28/16	44	0.76/0.79
Shuttle + Manned ILV	29/29	58	28/20	48	0.82/0.89 (0.98)[1)]

- For cargo, availability improvement with ILV vis-a-vis SHC3 probably does not justify the added development cost.
- A manned ILV supplementing Shuttle dramatically improves assured manned access.

1) dual compatible cargo or manned transportation

ORBITER PRODUCTION INTERVAL

In the longer term, the implication of Orbiter fleet attrition impels a review of replacement production planning. Ideally, production plans should anticipate losses for the planned life of the program.

Assuming a six year production lead time, 2 Orbiters should be in production at all times and 14 Shuttle launches per year, it is evident that the 14 per year case is already at risk. Some degree of production overlap is desirable even at 5 launches per year, but the lower fleet size requirement provides inherant spares in the interim.

ORBITER PRODUCTION INTERVAL

Probability of loss	0.022	
Frequency of loss		
Number of flights between losses	45	
Years, at 14 flights per year	3.2[1)]	
Required fleet size	4	Orbiters
Years, at 5 flights per year	9.1[1)]	
Required fleet size	2	Orbiters

- For a six year production lead time
  - / with a Shuttle launch rate of 14 per year, 2 Orbiters should be in production at all times
  - / some degree of production overlap is desirable even at 5 launches per year

1) excludes standdown time

SAMPLE SENSITIVITY ANALYSIS
EXPECTED SUCCESSES AND FAILURES

The event probabilities outlined in the prior charts focus on mean values. As noted in the subsystem failure rate derivations, a range of values is appropriate to address uncertainties in interpreting historical data and projected probabilities for future systems, and, indeed, ranges were used in Monte Carlo simulations treated earlier in the report. It is estimated that, based on these ranges, the probability of Orbiter loss could vary by plus or minus 0.01 around the 0.022 nominal value for a Shuttle flight.

The expected number of successful missions and total Orbiter losses during the five year model varies considerably with variation in per launch loss probability. However, the most significant observation is that even with the lowest assumed loss probability (highest reliability), expected Orbiter losses are sufficiently high to require continued Orbiter production to maintain the fleet. Expected successful launches would be slightly higher for the Shuttle plus ILV fleet compared to the Shuttle plus SHC3 fleet due to the differences in vehicle interdependence. However, the expected Orbiter losses would be approximately the same. Therefore, the need for continuing Orbiter production is general so long as the Shuttle remains the primary launch vehicle for deployment and support of the Space Station.

SAMPLE SENSITIVITY ANALYSIS
EXPECTED SUCCESSES AND FAILURES

FLEET RELIABILITY	PROB. OF ORBITER LOSS	PLANNED LAUNCHES Vehicle	PLANNED LAUNCHES Total	SUCCESSFUL LAUNCHES Vehicle	SUCCESSFUL LAUNCHES Total	UNSUCCESSFUL MISSIONS	ORBITER LOSSES
Shuttle Only							
Low	0.03	70/-	70	39/-	39	3.0	1.5
Nominal	0.02	70/-	70	46/-	46	2.3	1.1
High	0.01	70/-	70	56/-	56	1.0	0.6
Shuttle + SHC3							
Low	0.03	41/17	58	30/13	43	2.8	1.1
Nominal	0.02	41/17	58	34/14	48	2.0	0.8
High	0.01	41/17	58	38/14	52	0.8	0.4

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SUMMARY

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SUMMARY OF MISSION SUCCESS PROBABILITIES

- The expected number of launches between mission failures would be 20 and 48 for the Shuttle and the new vehicle respectively.

  / Although their respective subsystem failure probabilities are similar, engine-out capability from liftoff for a new vehicle reduces mission failure probability.

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SUMMARY OF PAYLOAD LOSS PROBABILITIES

Assuming a payload deployment mission[1)]

- o The frequency of payload loss is lower for Shuttle than for the best manned or unmanned new launch vehicle - 59 launches between losses versus 48 - due to their differences in capabilities to recover payloads in successful aborts.

- o During Space Station deployment, the odds of one or more Station module losses ranges from 1 in 1.9 for Shuttle only down to 1 in 2.7 for Shuttle + SHC3.

  / Contingency planning for loss of Space Station modules is required for all launch vehicle fleets analyzed.

1) e.g., a free flyer or Space Station cargo deployed immediately after reaching the mission orbit.

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SUMMARY OF ORBITER/MANNED VEHICLE LOSS PROBABILITIES

- Orbiter/manned vehicle loss probabilities are largely due to launch vehicle subsystem catastrophic failure probabilities, 0.016 for Shuttle and SHC3/ILV

- The major possibilities for reducing Orbiter/manned vehicle loss probabilities are

  - reducing catastrophic failure probabilities
  - providing escape capabilities from catastrophic failures

- Even though the mission failure probabilities for Shuttle and SHC3/ILV are substantially different, 0.05 vs 0.02, the total Orbiter/manned vehicle loss probabilities are substantially the same, 0.022 vs 0.021, due to the high effectiveness projected for Shuttle abort modes.

  - The expected number of launches between Orbiter and manned vehicle losses is 45 and 48 for Shuttle and SHC3/ILV respectively.

- Continued Orbiter production is required, but projecting production intervals is difficult.

  - The uncertainty in Orbiter loss probabilities, 0.01 to 0.03, leads to required production interval requirements ranging between 7 and 2 years for 14 launches per year.

  - Production intervals can be controlled with reduced Shuttle launch rates.

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FLEET PLANNED AND EXPECTED SUCCESSFUL LAUNCHES

5 YEAR MODEL

- The Shuttle planned and expected successful launches in the Space Station era are 66 and 46 respectively, a difference of 20 launches.
- For the mixed fleets, the planned launches are 56 with a range of expected successful launches from 46 for Shuttle + SHC2 to 50 for Shuttle + ILV.
- Increasing the numbers of planned launches of the supplementary launch vehicles would increase the numbers of expected successful launches and reduce Orbiter fleet attrition.
- Launch fleet commitments should be made on the basis of expected successful launches, not planned launches.

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FLEET LAUNCH VEHICLE AVAILABILITIES

- o Launch capabilities woudl not be available 10% to 20% of the time, due to the limitations of the individual launch vehicles and interdependency of Shuttle + SHC fleets.

- o For Shuttle + ILV fleets, the time unavailable could be reduced to 2% for the cases of

  / manned ILV which provides an independent manned launch capability

  / unmanned payloads which are dual manifested on Shuttle and ILV

- o The impact of supplementary launch vehicles on other operational risk parameters is minimal due to the limited flight rates assumed for them.

MAJOR MANNED PROGRAM RISKS/REDUCTIONS

From the standpoint of the manned space program, the critical operational risks are 1) Orbiter losses, 2) Space Station module losses, and 3) manned launch vehicle(s) availability (assured manned access). The results of this study lead to the following general conclusions:

Although the introduction of another launch vehicle to supplement the launch capabilities of Shuttle could reduce Orbiter attrition, it would not remove the requirement for a plan to continue Orbiter production to maintain the fleet.

None of the fleets analyzed would provide a substantial reduction in the probabilities of Space Station module losses during deployment. Accordingly, a contingency plan for module losses is essential to the viability of the program.

Any single launch vehicle may experience a launch failure which would cause it to be non-operational for a time that would jeopardize the safety of the crew and the operation of the Station. A second manned launch vehicle, independent of the Shuttle, has the most capability to reduce this risk. It also could serve to reduce Orbiter attrition by reducing its launch rate requirements. The introduction of such a vehicle, therefore, has the most potential for reducing the risk of the manned space program.

MAJOR MANNED PROGRAM RISKS/REDUCTIONS

RISKS	RISK REDUCTIONS	
	Supplementary Launch Vehicle	Other
o Orbiter losses	Off load Shuttle launches to another launch vehicle[1)]	Continue Orbiter production
o Space Station module losses	None	Establish a contingency plan for module losses
o Assured manned access to Space Station	Independent manned launch vehicle	None

[1)] use the Shuttle only where its capabilities are essential

FLEET RISKS WITH HIGH LAUNCH RATES

Study of fleet risks during the Space Station era naturally raises the question as to similar risks with traffic increase due to a large scale manned initiative. To examine the effect of increased launch rate, a 60 percent addition to the mixed fleet mission model by the turn of the century was projected. Two fleets are compared - a Shuttle/SHC3 mix and a Shuttle/manned ILV fleet. The SHC3 is unmanned.

A cursory analysis using the lower end of the nominal loss probabilities discussed earlier shows that the frequency of unsuccessful missions, payload losses and total manned vehicle losses (either Orbiter or the supplementary manned vehicle) would be approximately the same for all the Shuttle technology, highly interdependent fleet and the Shuttle/ILV fleet. However availabilities, Orbiter losses and facility requirements are drastically different. The Shuttle/SHC fleet faces frequent Orbiter losses and unacceptable availability. Vehicle independence within the latter fleet would permit very high assured manned access, while the frequency of Orbiter losses would be dramatically reduced with the assumed launch rates. Additionally, facilitation requirements would not be nearly as great. (A fleet with a manned SHC would reduce Orbiter losses but would not provide the other benefits. Availability for manned flight would remain low.)

Interdependent capability, with a balance of launch rates which considers potential cost of loss, clearly becomes a program imperative as launch rates increase.

FLEET RISKS WITH HIGH LAUNCH RATES

	SHUTTLE + SHC3 (Shuttle/SHC)	Total	SHUTTLE + MANNED ILV (Shuttle/Manned ILV/ILV)	Total	
Assumed Annual Traffic					
Baseline Manned	(6 / 0)	6	(6 / 0 / 0)	6	
New Mission Manned	(8 / 0)	8	(/ 8 / 0)	8	
New Mission Cargo	(0 / 4)	4	(0 / 0 / 4)	4	
Total	(14 / 4)	18	(6 / 8 / 4)	18	
Years Between					
Unsuccessful Mission		1.3		1.8	
Payload Loss		3.1		2.8	
Orbiter Loss		**3.2**		**7.6**	
Manned Vehicle Loss (Total)		3.2		3.2	
Availability					
Shuttle		**0.46**		0.79	**0.96**[1]
SHC OR ILV		**0.46**		0.83	
Required Facilities Capability (Launches/Yr)					
Shuttle Facilities		**39**		**8**	
New Facilities		-		**15**	

[1] Manned access and dual compatible cargo

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EFFECTIVE RISK REDUCTION EFFORTS

o A launch vehicle with subsystem independence from Shuttle and with manned capability has the greatest leverage in reducing risks to the manned space program in the Space Station era and beyond.

o Development consideration should emphasize

/ A new manned vehicle (PLS or ACRC with ascent capability)

/ A new main engine (STME)

/ Independent boosters (ASRM and RSRB or LRB and ASRM)